Detection Performance of Active Sonar Based On Underwater Acoustic Communication Signals

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***Abstract*—A new system of integrated detection and communication is put forward, which detected echoes of the communication signal reflected by target. As we all known, different underwater acoustic modulation modes produce different communication waveforms. The detection performance of three conventional single-carrier underwater acoustic modulation signals of MSK、2FSK and BPSK are analyzed by comparing their ambiguity functions and Q-functions. Having established the target echo model of underwater acoustic wireless modulation signal, the target estimation performance using different modulation signals are analyzed by employing the conventional beamforming and multiple signal classification algorithms.・The results will instruct the waveform design for the integrated system of detection and communication.**

Keywords—The integrated system of detection and communication；active sonar；underwater acoustic Wireless modulation；ambiguity function；target estimation.

I. INTRODUCTION

Underwater acoustic detection as the typical ways of underwater information acquisition, processing, transmission and exchange have a certain relation with Underwater acoustic communication, which making it possible to combine the independent two system.

The early research of the integrated system of underwater acoustic detection and communication started from the integrated system of radar and communication. The Working pattern of integrated system of radar and communication can be divided into three types of time-sharing systems, beam splitting system and simultaneous system, the simultaneous system as the most concerned system among them can mainly divided into three forms.

Table 1 The simultaneous system

The integration of underwater acoustic detection and communication base on the simultaneous system	Superposition of communication signal and detection signal	**Advantage:** Independtly designed waveform. **Disadvantage:** Interference between signals, low power utilization and difficult separation of receiver signals
	Intergrated signal design based on detection signals	**Advantage:** The detection performance is guaranteed. **Disadvantage:** The direction of communication is limited by the direction of the beam and the data rate of the communication is affected.
	Intergrated signal design based on communication signals	**Advantage:** The communication performance is guaranteed. **Disadvantage:** The low sound source level affects detection distance, and the long pulse wide produces detection blind area.

For the research of simultaneous system, Christian Sturm et al. studied the application of OFDM in the integrated system of vehicle radar and communication [1][2]. They make use of the frequency domain characteristics of OFDM signal to estimate the distance of target by Fourier transform, which not only fast, low side lobe, but also independent of modulation data. However, OFDM signal only can be used of short distance communication or detection because of it has disadvantage of undulates terribly and larger peak, such as distance measurement and communication in intelligent transportation. The integrated presented that an integrated signal of radar and communication which based on MSK direct sequence spread spectrum have better autocorrelation through spreading the digital baseband signal in communication [3], so as to meet the requirements of radar detection. The integrated analyzes the ambiguity function performance of the same code multi-carrier frequency phase coding and sub-carrier coding cyclic shift MCPC as radar waveform [4],which based on the orthogonal multi-carrier waveforms that have been maturely used in communications. On this basis, a comprehensive waveform design method is proposed to control the shift number of the MCPC signal by using of subcarrier phase encoding with random communication data and the incompatibility problem between the random communication signal and the deterministic radar signal has been solved.

The existing research on the integrated system of communication and detection is mainly applied to radar, it also has reference significance for the integrated system of underwater detection and communication. In this paper, three conventional modulation signals in underwater acoustic communication are selected and established the echo model through analyze the ambiguity function [5] and Q-function, and compared the detection performance and communication error rate of those types of modulated signals, which provide support for the integrated composite waveform design.

II. ACTIVE SONAR SIGNAL

A. *Signal Classified*

The pulse form is the mainly form of the conventional active sonar signal, which has a high resolution of range and speed. For the integrated system of underwater acoustic communication and detection, the active signal is a communication signal, which is generated by the modulation of the transmission information. And the modulations modes are different result in the waveforms of communication signal are different.

a. Conventional Active Sonar Signal

The CW signal that is called for a single frequency rectangular pulse signal is widely used in active sonar due to

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it has advantage of easily generated and transmitter structure simple. Its time function is expressed as:

$$u(t)=\frac{1}{\sqrt{T}}rect(\frac{t}{T})\mathrm{e}^{j2\pi f_0 t} \quad t\in[0,T] \tag{1}$$

Where T is the pulse width and f_0 is the signal carrier frequency. Its ambiguity function is as follows

$$|\chi_{\mathrm{CW}}(\tau,\ f_d)|=\begin{cases}(T-|\tau|)\left|\dfrac{\sin[\pi f_d(T-|\tau|)]}{\pi f_d(T-|\tau|)}\right| & (|\tau|\le T)\\ 0 & (|\tau|>T)\end{cases} \tag{2}$$

The time resolution of CW signal is 0.3T and the frequency resolution is 0.44/T. LFM signals are used in active sonars, which have better time resolution. The time function of LFM signal is expressed as follows

$$s(t)=\mathrm{rect}(\frac{t}{T})\mathrm{e}^{j\pi(2f_0t+kt^2)} \quad t\in[-\frac{T}{2},\frac{T}{2}] \tag{3}$$

Where f_0 is carrier frequency and $k=B/T$ is the frequency modulation slope, and its ambiguity function is as follows

$$|\chi_{\mathrm{LFM}}(\tau,f_d)|=\begin{cases}\left|\dfrac{\sin[\pi(f_d-k\tau)(T-|\tau|)](T-|\tau|)}{\pi(f_d-k\tau)(T-|\tau|)}\right| & |\tau|<T\\ 0 & |\tau|\ge T\end{cases} \tag{4}$$

The time resolution of LFM signal is 0.44/B, frequency resolution is 0.44/T, and the shape of its ambiguity is Oblique blade.

b. Underwater Acoustic Wireless Modulation Signal

The modulation technology of underwater acoustic communication is basically similar to wireless communication, and its technology is mostly derived from wireless communication. The conventionally modes of underwater acoustic wireless modulation include frequency shift keying (FSK), phase shift keying (PSK), minimum frequency shift keying (MSK), and multi-carrier orthogonal frequency division multiplexing (OFDM). These characteristics are shown in the following table

Table 2 Basic Acoustic Wireless Communication Modulation

Modulation	Characteristics
FSK	Strong anti-interference capability ; wide band occupancy; low channel requirement; suitable for medium-distance transmission
PSK	Strong anti-interference capability ; high frequency band utilization; low system complexity
MSK	Enveloping constant; continuous phase; strictly orthogonal; out-of-band power density drops rapidly
OFDM	High transmission rate; high bandwidth utilization; strong anti-multipath capability ; sensitive to Doppler; high peak-to-average power ratio

Three single carrier modulation modes are selected to analysis their performance.

The initial phases "0" and "π" are usually used to respectively represent binary "0" and "1" with the BPSK modulation mode. Therefore, the time domain expression of BPSK signal is as follows

$$X_{2PSK}(t)=A\cos(2\pi f_c t+\phi_n) \quad \phi_n=\begin{cases}0 & \text{when "0" is transmited}\\ \pi & \text{when "1" is transmited}\end{cases} \tag{5}$$

The 2FSK modulation mode uses a binary digital baseband signal to control the frequency of the sinusoidal carrier. There are two states of binary symbols: "1" and "0", and the corresponding carrier frequency can be set as f_1 and f_2.The time domain expression of 2FSK is as follows

$$X_{FSK}(t)=\begin{cases}A\cos 2\pi f_1 t & (n-1)T_b<t\le nT_b \ \text{"1"is transmited}\\ A\cos 2\pi f_2 t & (n-1)T_b<t\le nT_b \ \text{"0"is transmited}\end{cases} \tag{6}$$

The minimum frequency shift keying (MSK) signal occupies wider bandwidth than BPSK, which means that the frequency band utilization is lower. It is a FSK signal with constant envelope, continuous phase, minimum bandwidth, and strict orthogonally. The k_{th} symbol of the MSK signal can be represented as:

$$X_k(t)=A\cos(\omega_c t+\frac{a_k\pi}{2T_s}t+\phi_k) \quad kT_s<t\le(k+1)T_s \tag{7}$$

Where $\omega_c=2\pi f_c$, $a_k=\pm1$, when the input code element is "1", $a_k=+1$,When the input code element is "0", $a_k=-1$, T_s is the width of the code element.

B. *Ambiguity Function Analysis*

The selection of active sonar signal waveform is related to the receiver's processing method. The matched filtering is widely used by receivers, and the ambiguity function has a certain relationship with the matched filter, so the detection performance of the signal can be invested by analyzing the ambiguity function of the signal. The ambiguity function is defined as follow

$$\phi(\tau,f_d)=|\chi(\tau,f_d)|^2\cong\left|\int_{-\infty}^{\infty}u(t)u^*(t+\tau)e^{j2\pi f_d t}dt\right|^2 \tag{8}$$

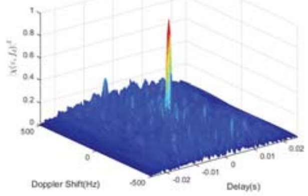
The ambiguity function is used to analyze a resolution of range and speed of the system under the condition of using the best information processing. Therefor the ambiguity function can help us choose a reasonable transmit waveform.

Follow the ambiguous function analysis of underwater acoustic wireless modulation signals are performed individually.

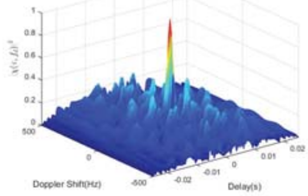
Table 3 Assumed Simulation Parameters

center frequency	6kHz
carrier frequency	6kHz
sampling frequency	48kHz
bandwidth	4kHz
signal duration	25ms
the number of symbols	100
the symbol width	12

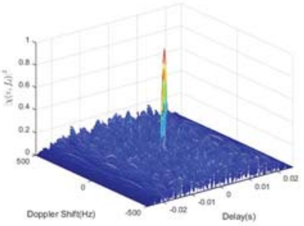
Using the above parameters, the following results are obtained.



（a）MSK



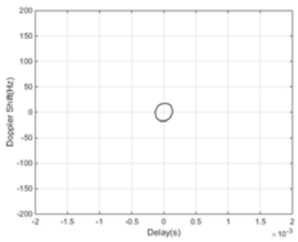
（b）2FSK



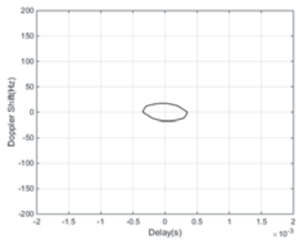
（c） BPSK

Figure 1 the Ambiguity Function Figure of Different Signals

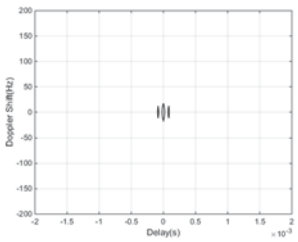
At 0.707 times of the ambiguity function figure, we can get a cross section figure which reflects the signal's capability to distinguish the frequency shift and time delay of the adjacent targets, and reflects the measurement accuracy of the target distance and speed. According to the ambiguity function figure of Fig. 3, the cross-sectional view is obtained as follows



（a） MSK



（b） 2FSK



（c） BPSK

Figure 2 the Cross-Sectional View of Different Signals

The ambiguous function of the conventional active sonar signal is "blade shape " , but the CW signal cannot obtain high resolution of time and frequency at the same time. The Doppler sensitivity of the LFM signal is positively correlated with the bandwidth. From the ambiguity function figure and the cross-sectional view, for the wireless modulation signal, the ambiguity function of the MSK and 2FSK modulation signals are “pushpin shape”, with the high resolution of time and frequency. The ambiguity function of the BPSK modulation signal is “pin plate shape” and has strong anti-Doppler reverberation capability.

C. Anti-reverberation Performance Analysis

The underwater reverberation is formed by the superposition of the scattering points at the receiving points, which is caused by the inhomogeneity of the underwater environment and the scattering of the transmitted signal [7]. For the active sonar system, reverberation is the main background interference in the shallow sea environment. So the anti-reverberation performance is important for the active sonar signal.

The Q-function is the integrated system of the square of the ambiguity function along the distance dimension. Its physical meaning is that the energy convolution of the reverberation echo generated by the scattered at all distances after the matched filtering, and its function form is as follows:

$$Q(f_d) = \int_{-\infty}^{\infty} \left|\chi(\tau, f_d)\right|^2 d\tau \qquad (9)$$

It is used to measure the anti-reverberation capability of different signals. The smaller function value is, the smaller the reverberation intensity of the output is, and the more favorable for the detection of targets under reverberation constraints. For the conventional active sonar signals and underwater acoustic modulation signals, compared their Q-function, the simulation condition is the same as above. The Q-functions of different signal types are shown as follow:

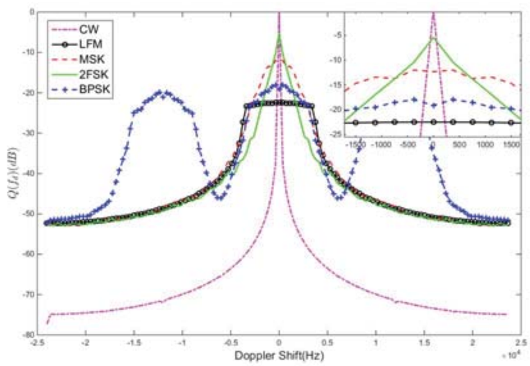


Figure 3 The Q-function of Different Signal Types

From Figure 3, when the Doppler is in the vicinity of zero, the Q-function of the CW signal is the highest, and the LFM is the lowest. With the same bandwidth and transmission rate for the wireless modulation signal, when the Doppler is in the vicinity of zero, the Q-function values of the three modulation modes of FSK, MSK, and BPSK decrease sequentially, and the anti-reverberation capability gradually increases. As the Doppler frequency shift increases to the range of 1.1-4.8 kHz, the Q-function value of the FSK modulated signal is smaller than that of MSK and BPSK, and it has better anti-reverberation capability. For underwater acoustic wireless communication, the bandwidth is limited and the frequency is low, and the Doppler frequency shift is usually less than 1 kHz. Therefore, compared with the three modulation modes, the BPSK modulated signal has the best anti-reverberation performance.

III. DETECTION PERFORMANCE ANALYSIS

In order to further analyze the difference in the detection performance of different modulation modes, the communication signals of MSK, 2FSK, and BPSK modulation are used as active transmission signals to analyze the detection and estimation performance.

A. Array Receiving Model

Assuming that the active sonar transmitting signal is $s_0(t)$, the target echo signal is formed by reflection signal when the target is irradiated, and the echo signal is time-delay, Doppler frequency shift and amplitude change compared with the original signal. So the echo signal can be expressed as follow:

$$S(t) = As_0(t-\tau)e^{j2\pi f_d t} + n(t) \tag{10}$$

Where τ is the delay, f_d is the Doppler shift, $n(t)$ is the Gaussian white noise. The uniform line array of M sensors is used to receive source that the incident angle is $\theta_{\mathrm{k}}(\mathrm{k}=1,2,\cdots,\mathrm{K})$ in the far field, as shown in the following figure:

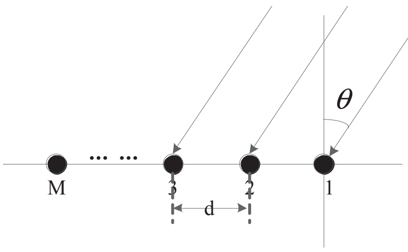


Figure 4 the uniform line array

The spacing of each sensor is d, and response vector can be expressed as:

$$\mathbf{a}(\theta_k)=\left[1 \quad \exp(-j2\pi\frac{d}{\lambda}\sin\theta_k) \quad \cdots \quad \exp(-j2\pi(M-1)\frac{d}{\lambda}\sin\theta_k)\right] \tag{11}$$

Where s is the wavelength, so the steering vector is as follows:

$$\mathbf{A} = \left[\mathbf{a}(\theta_1) \quad \mathbf{a}(\theta_2) \quad \cdots \quad \mathbf{a}(\theta_k)\right] \tag{12}$$

From the above formula, we can get the array receiving model

$$\mathbf{X}(t) = \mathbf{AS}(t) + \mathbf{N}(t) \tag{13}$$

B. Performance Analysis

The conventional active sonar signal is usually fixed, but the communication signal needs to be changed according to the transmitted information, if used the communication signal as the active sonar signal, the detection performance will be fluctuations. The simulation condition is the same as above, four groups of symbols are randomly generated, which the signal-to-noise ratio is -10 dB and target orientation is [−5°, 5°], and using the MUSIC method to estimate DOA.

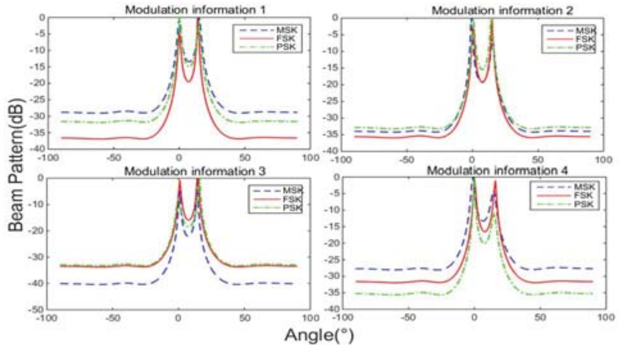


Figure 5 the beam-patterns of a linear array consisting of 8 sensors with random transmitted symbols

From the above figure, it can be seen that the random symbol information causes the difference of the modulated signal waveform, thus affecting the detection performance. In order to further study the detection performance of different modulation modes, Monte Carlo experiments were used.

The resolution probability is an important criterion for the target azimuth estimation, which means that in some Monte Carlo experiments, the probability of two or more targets can be correctly identified, and the correct resolution needs to satisfy the following conditions:

$$\max\left\{\left|\hat{\theta}_1-\theta_1\right|,\left|\hat{\theta}_2-\theta_2\right|,\cdots,\left|\hat{\theta}_k-\theta_k\right|,\cdots\left|\hat{\theta}_K-\theta_K\right|\right\} \le \frac{BW}{2} \tag{14}$$

In other words, the absolute value of the difference between each target azimuth estimate and the corresponding true azimuth value is less than half of the beam width. The error analysis of the azimuth estimations is based on the root mean square error, which is $RMSE = \sqrt{\mathrm{MSE}}$ .Where the mean square error MSE is defined as follows:

$$MSE \approx E[(\hat{\theta}-\theta)^2] = [\theta - E(\hat{\theta})]^2 + E\{[\hat{\theta}-E(\theta)]^2\} \tag{15}$$

In the above formula, θ and $\hat{\theta}$ are the true values and estimated values of target azimuth respectively. The simulation condition is the same as above, and two target azimuth are [-7°, 7°]. The Monte Carlo experiments were performed with the conventional beamforming and MUSIC algorithms. We can get the following results:

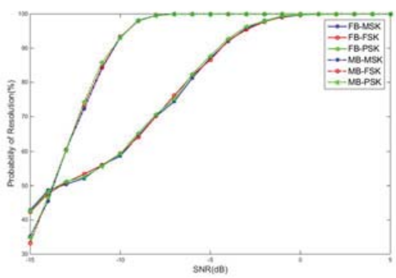


Figure 6 Successful detection probability

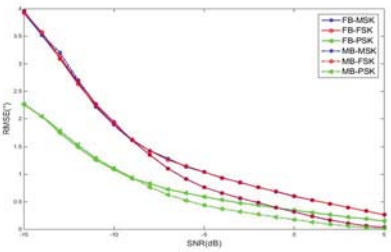


Figure 7 Mean Square Error

It can be seen from the simulation results that, the resolution probability and the mean square error of the three modulation modes are the same under the same simulation conditions, and the different estimation methods have different estimation performance.

C. Bit Error Rate

The system of integrated detection and communication based on communication signals，and without affecting the communication performance. Therefore, the communication performance of the integrated system is important, and the BER is an important measure of the performance communication. For 2FSK and BPSK modulation, the theoretical BER is as follows:

Table 4 the theoretical BER

Demodulation / Modulation	coherent demodulation	noncoherent demodulation
2FSK	$\frac{1}{2}erfc(\sqrt{\frac{r}{2}})$	$\frac{1}{2}e^{-r/2}$
BPSK	$\frac{1}{2}erfc(\sqrt{r})$	/

When each orthogonal component is received by the matched filter, the performance of the MSK signal is the same as that of BPSK, QPSK and OQPSK. If it is demodulated with the correlation demodulation modes as a FSK signal, its performance is 3dB worse than that of 2PSK [5]. The theoretical bit error rate for various modulation modes is shown in the following figure:

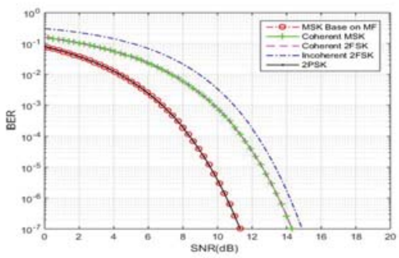


Figure 8 theoretical error rate of different modulation modes

From the above figure, PSK has a lower bit error rate than 2FSK. When the MSK signal receives each quadrature component with a matched filter, the BER is lower than 2FSK. If it is regarded as an FSK signal to used correlation demodulation modes, it has the same bit error rate as 2FSK but less than incoherent 2FSK. In general, the BER of the PSK is smaller, followed by MSK, and 2FSK is larger.

The actual bit error rate is simulated, and the bit error rate is analyzed based on the preceding simulation conditions, as shown in the following figure.

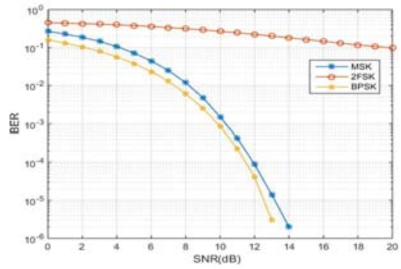


Figure 9 simulation error rate of different modulation modes

Under this simulation condition, the BER of BPSK is the lowest, followed by MSK, and the BER of 2FSK is the largest. Because the symbol width is too small, it causes 2FSK failure. Therefore, when the symbol width is low, 2FSK is not suitable to choose, and BPSK and MSK are optional.

IV. CONCLUSION

The active detection using the communication transmission signal has been studied in this paper, where different modulation modes are considered, including MSK, 2FSK, and BPSK. Their anti-reverberation capabilities and estimation precisions were compared. The ambiguity functions of the MSK and 2FSK modulation signals were "pushpin shape" and the shape of the BPSK modulation signal was "pin plate shape", there were all had a high resolution of time and frequency. Through the Q function analysis, the Q-function value of FSK, MSK, and BPSK decrease sequentially, and the anti-reverberation capability gradually increases along with the value of Doppler shift. Under the situation of the same bandwidth, sampling rate, transmission rate and the same others, the three modulation modes had the same estimation performance. And according to the theoretical error rate, the PSK is smaller, the MSK is the second, and the 2FSK is largest. Finally, it is anticipated that a basis of waveform design for the integrated system of underwater acoustic detection and communication can be provided by analyzing the above performance.

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